Combining modeling and measurements to control the AC losses in coated conductors

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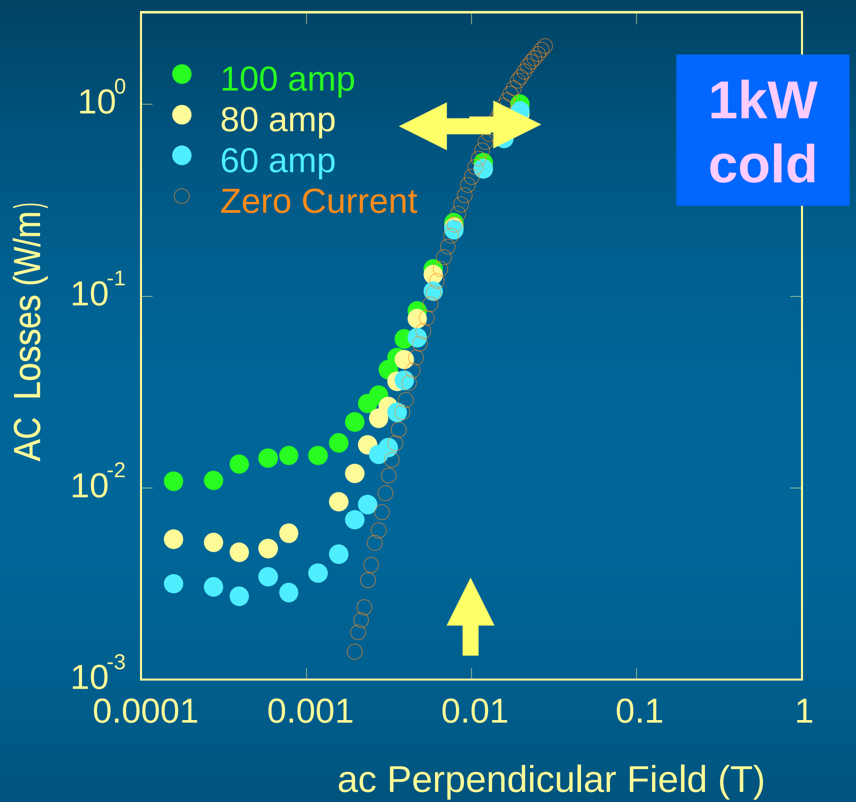
AC losses are a problem

- Changing field and/or current dissipates energy in coated conductors
- Need to remove this energy (heat) by refrigeration
  - Economic problem
  - Engineering problem
- Losses are significantly higher than we would like
- In particular
  - Losses due to ac fields perpendicular to tape face
- Need to 'develop' the conductor
  - Simply increasing Ic will not do it



eg Coil: 10km of tape
10% in perpendicular field of 10mT

There *are* techniques for reducing ac losses

- Reduce losses at both the conductor and the coil level
- Numerical simulations are a reliable and powerful tool to help us do this
- Need to couple with experiment
- LANL has implemented an integrated numerical and experimental program unique in the US

Outline

- Why numerical models?
- We have combined modeling and measurements in order to understand and reduce ac losses
  - ‘Standard’ individual tapes
  - A method for loss reduction on individual tapes
  - Assemblies of tapes (vertical stack, coils)
- Chosen to work with a commercial FEM package (FLUX3D)
  - Allows easy dissemination of expertise
  - Building from verified package
  - Efficient use of resources

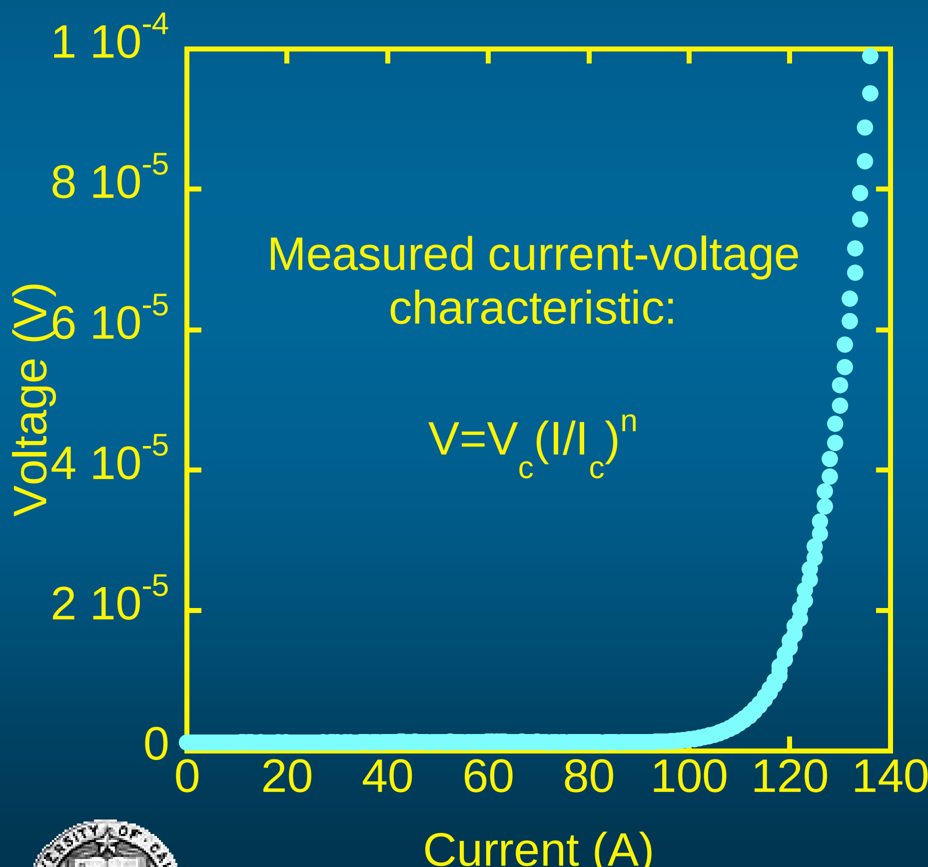
Numerical models are more realistic than analytical

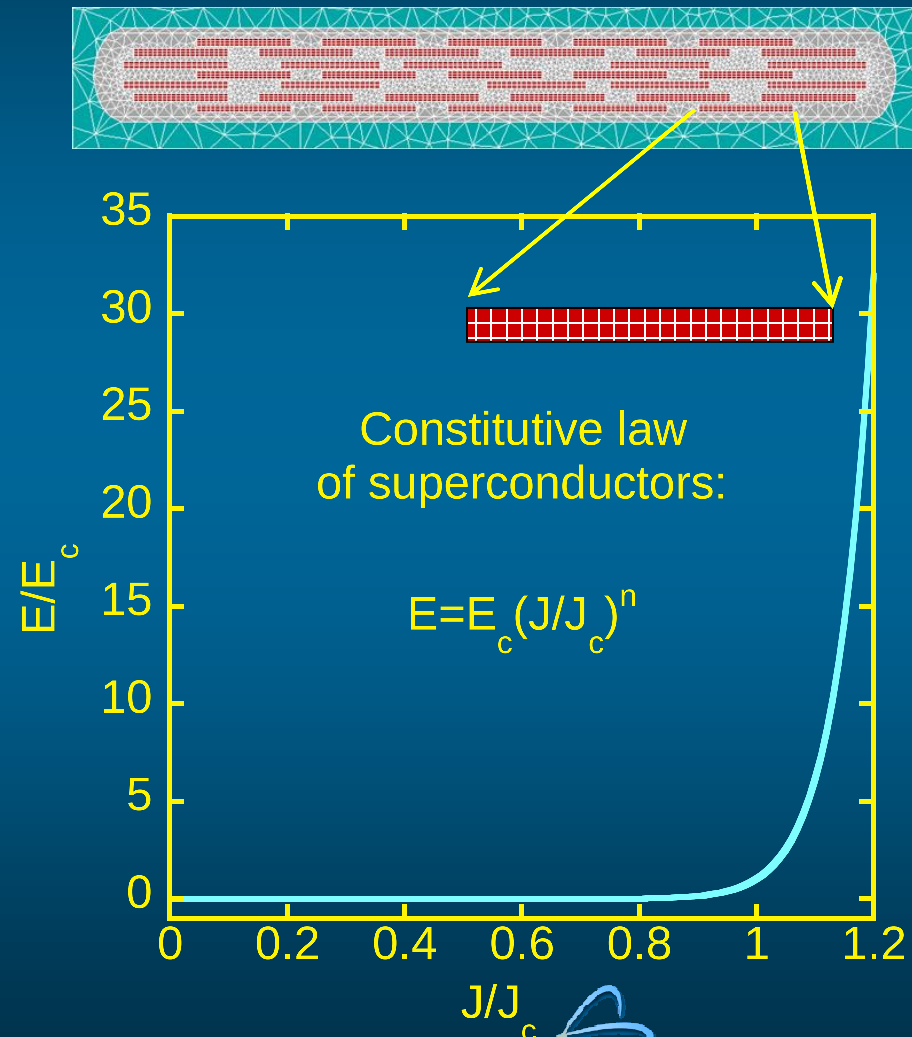
- Evaluation of ac losses before the implementation of SC devices
- Simplest method: analytical models
  1. Inaccurate description of V-I characteristics (Critical State Model)
  2. Simple geometries
  3. Individual tapes or infinite number of tapes
- Finite Element Method (FEM):
  1. Smooth V-I characteristics
  2. Non-constant Jc, e.g. Jc(B), Jc(x,y,z)
  3. More realistic geometries
  4. Interaction between finite number of tapes

FEM used successfully for BSCCO tapes

- Solves Maxwell's equations for transient problems
  - Geometry discretized into a grid of elements
  - Equations solved at every point of the grid
  - Computation of electromagnetic quantities
- Superconductors' behavior
  - non-linear E-J power-law: $E(J)=Ec\,(J/Jc)^n$
  - Jc(B), Jc(x,y,z)

How we pass from reality to model



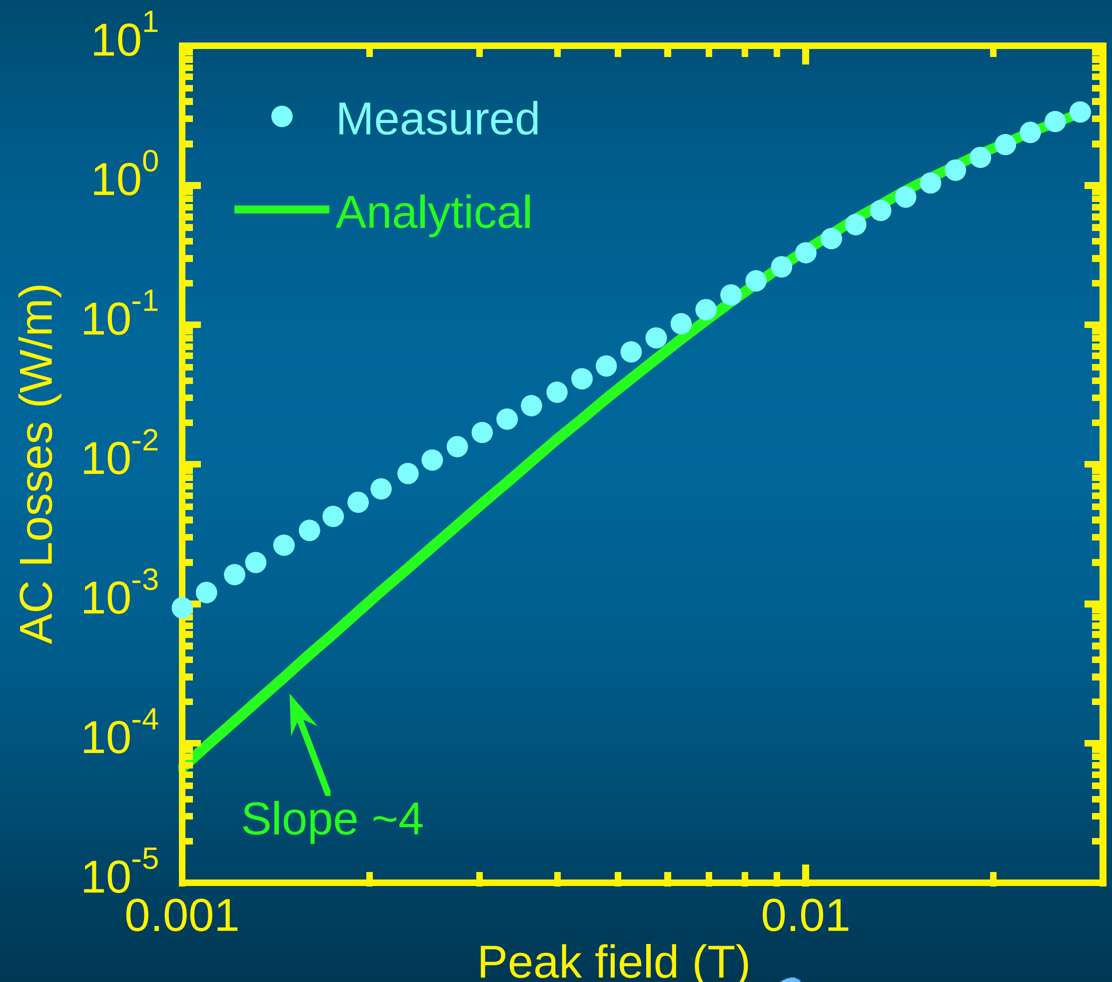


Where are the FEM people?

- Expertise previously only overseas
  - Yokohama National University, Japan
  - Swiss Federal Institute of Technology - Lausanne, Switzerland
  - University of Southampton, UK
- Little previous effort in USA
- At LANL powerful combination of experimental and modeling expertise

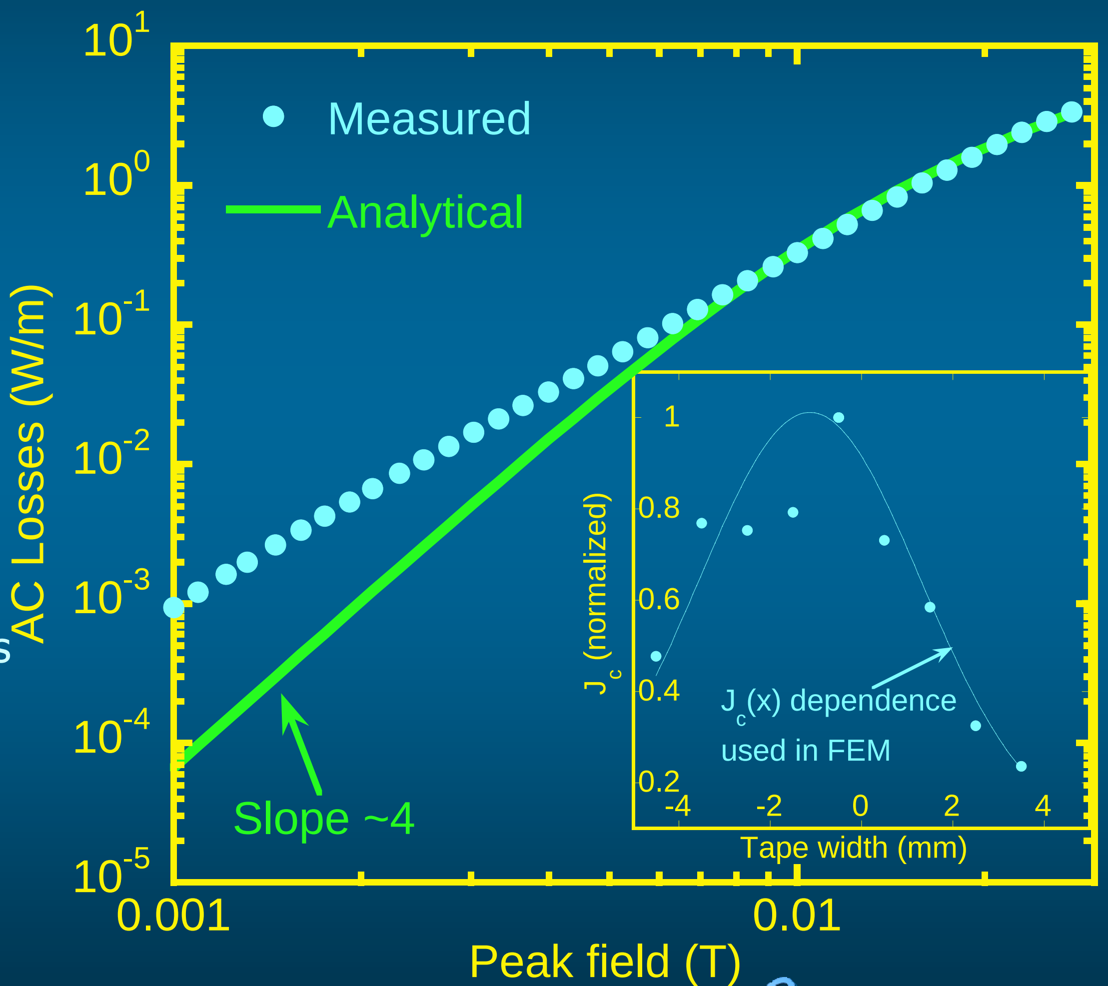
Magnetic losses of individual tapes - characteristics

- Analytical model and FEM (const. Jc)
  - **P ~ B⁴** for fields below penetration
- Experimental results on varied samples
  - lower slope, typically 3-3.6



Magnetic losses of individual tapes - characteristics

- Analytical model and FEM (const. Jc)
  - **P ~ B^4** for fields below penetration
- Experimental results on varied samples
  - lower slope, typically 3-3.6
- Hypothesis
  - non-uniform Jc across tape
- Test
  - FEM with Jc(x) agree with experiments
  - DC critical current measurements



Magnetic losses of individual tapes - characteristics

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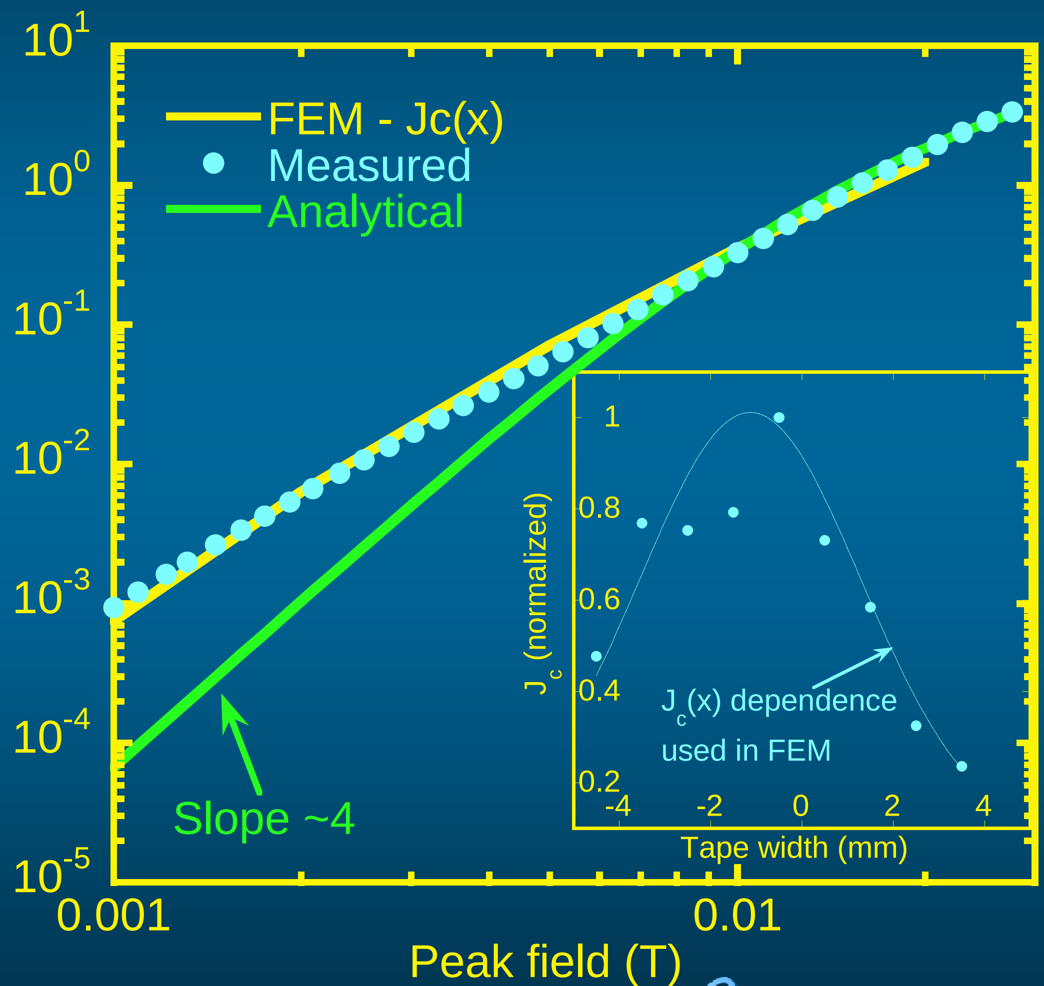
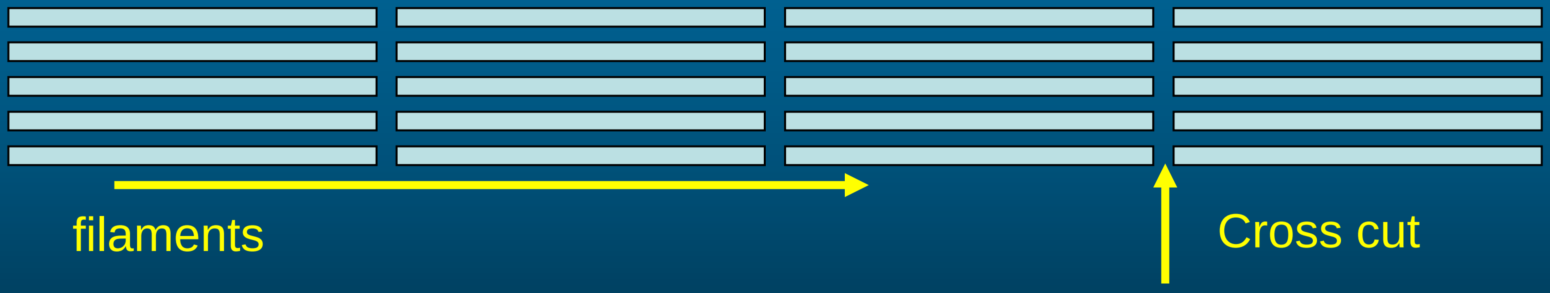
- Conclusions:
  - Tapes are not uniform
  - FEM works



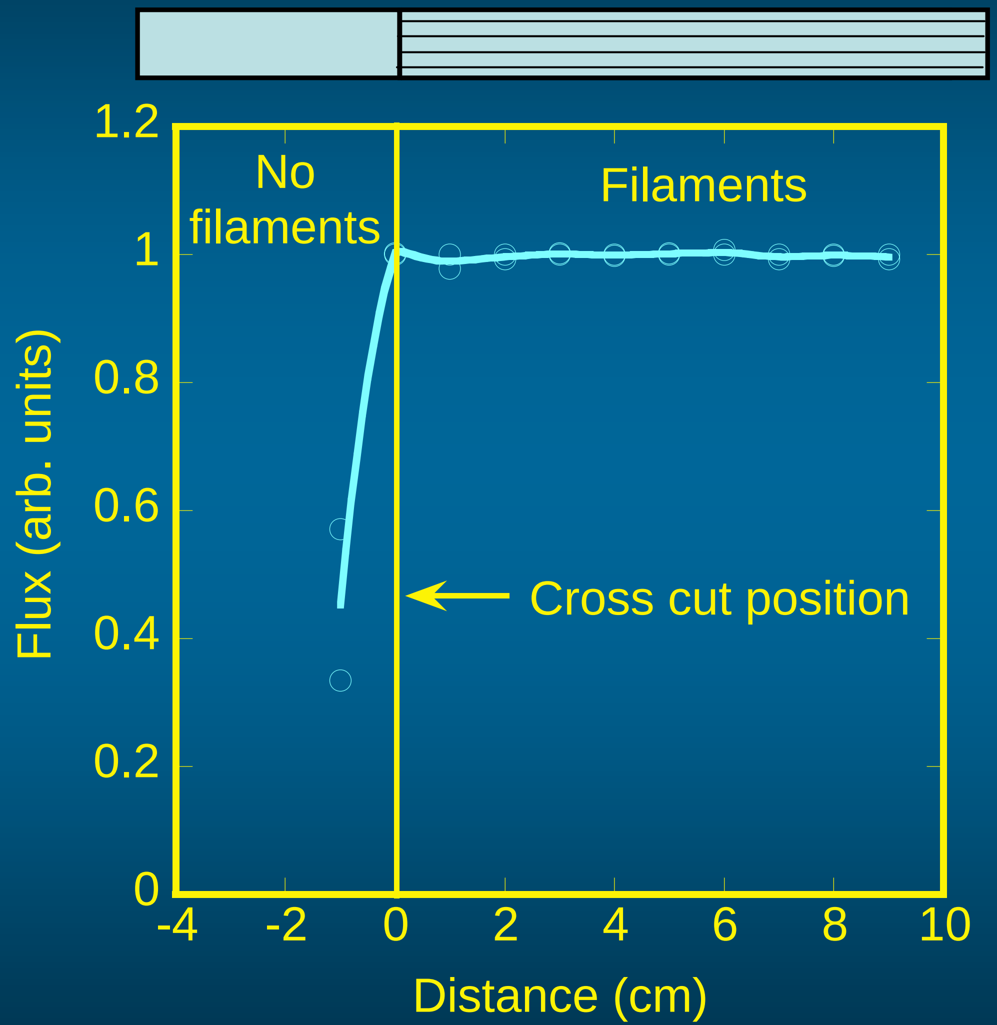
Reduce losses of individual tapes by filaments and cross cuts

- Losses inversely proportional to the square of the width
- Multifilamentary tapes
- The filaments must experience the same electromagnetic environment → transposition…not easy in practice!
- Alternative way: striate the superconductor into filaments AND periodically break the filaments with transversal cross-cuts
- Magnetic flux can enter between the filaments

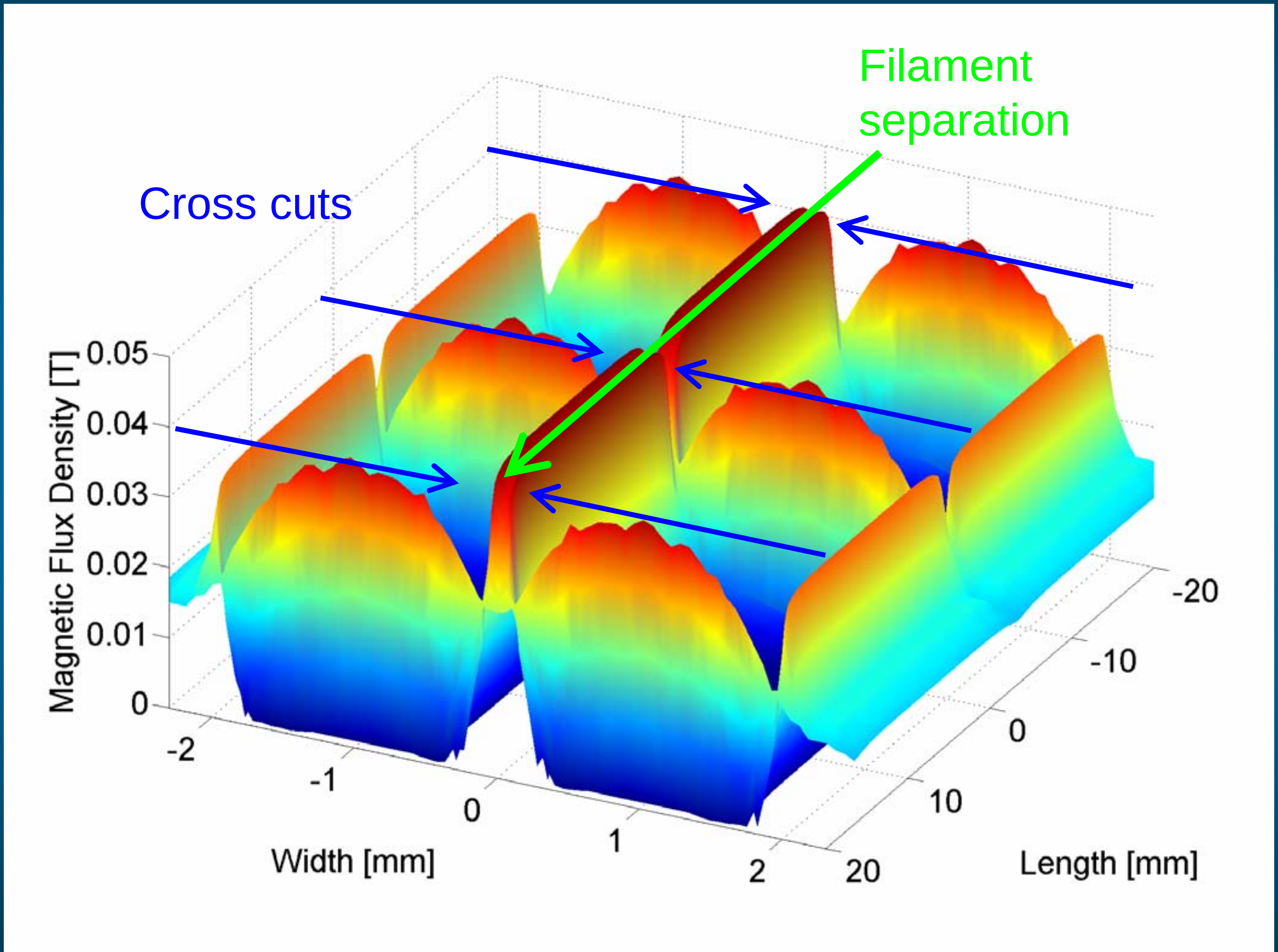


Flux can travel many cm from a cross-cut during an ac cycle

- Experiment
  - 100 Hz perpendicular ac field, 10 filaments
  - Flux can only enter at the cross-cut
  - Measure flux between filaments
  - Function of distance from entry point
- On the left of the cross-cut no flux in the sample
- In the filament region
  - Flux moves at least 10 cm in a cycle
- 5 cuts/m sufficient for loss reduction at 60 Hz

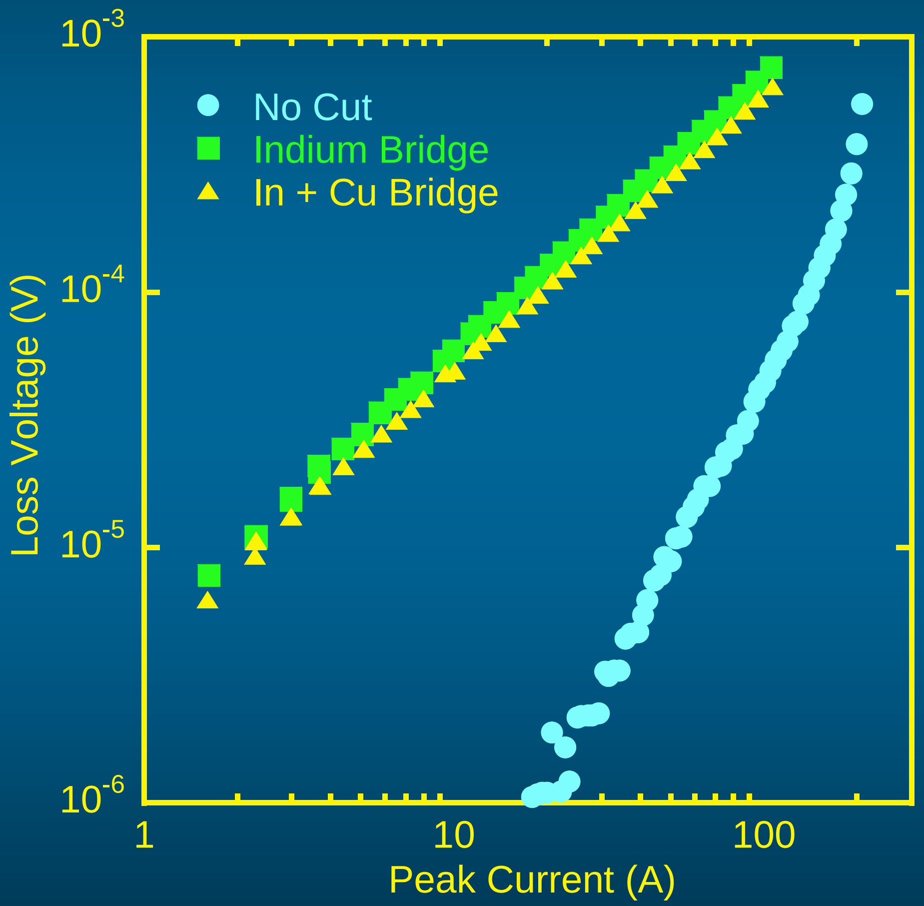


FEM analysis confirms the effect



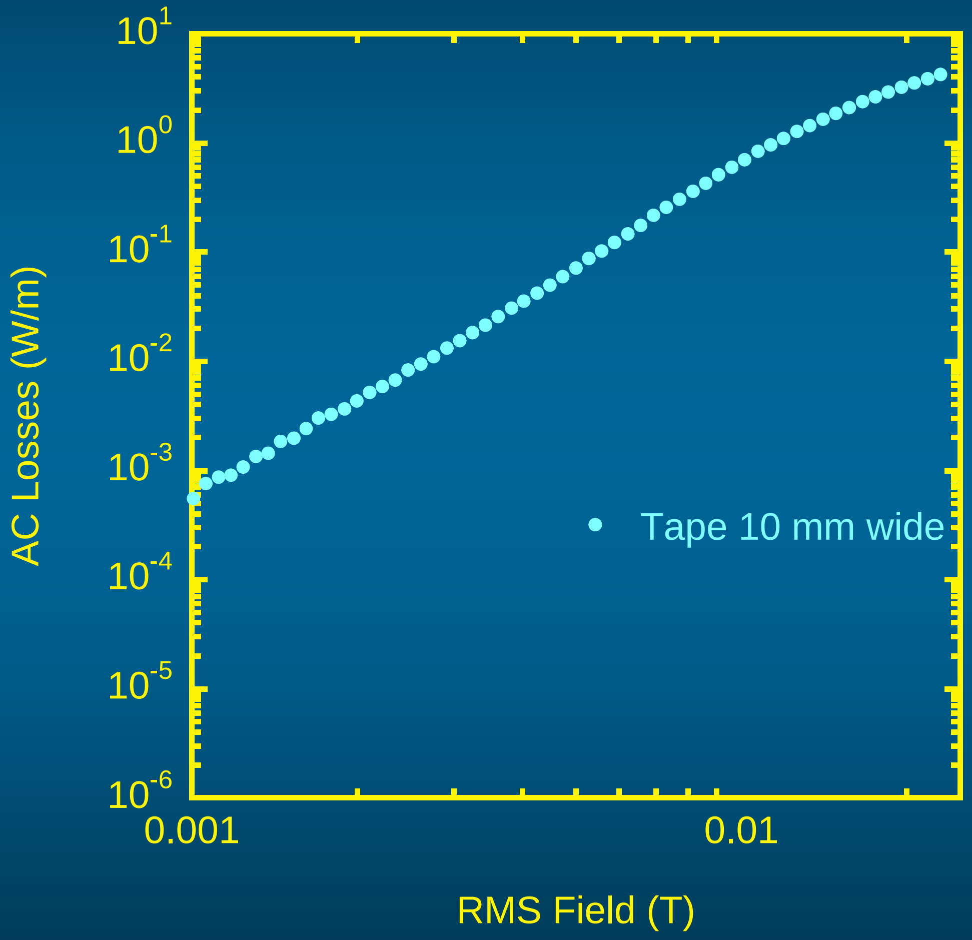
Normal metal bridge allows transport current

- Necessary to bridge the cross-cuts with normal metal
- Two types of experimental bridge
  - indium solder (50μm)
  - indium+ 25μm copper
- These bridges produce a resistance of 4 μΩ for a 4 mm wide tape
- This produces ohmic loss
- The ohmic loss is significantly higher than the ac transport loss in the superconductor
- Increase in ohmic losses is outweighed by decrease in magnetic losses



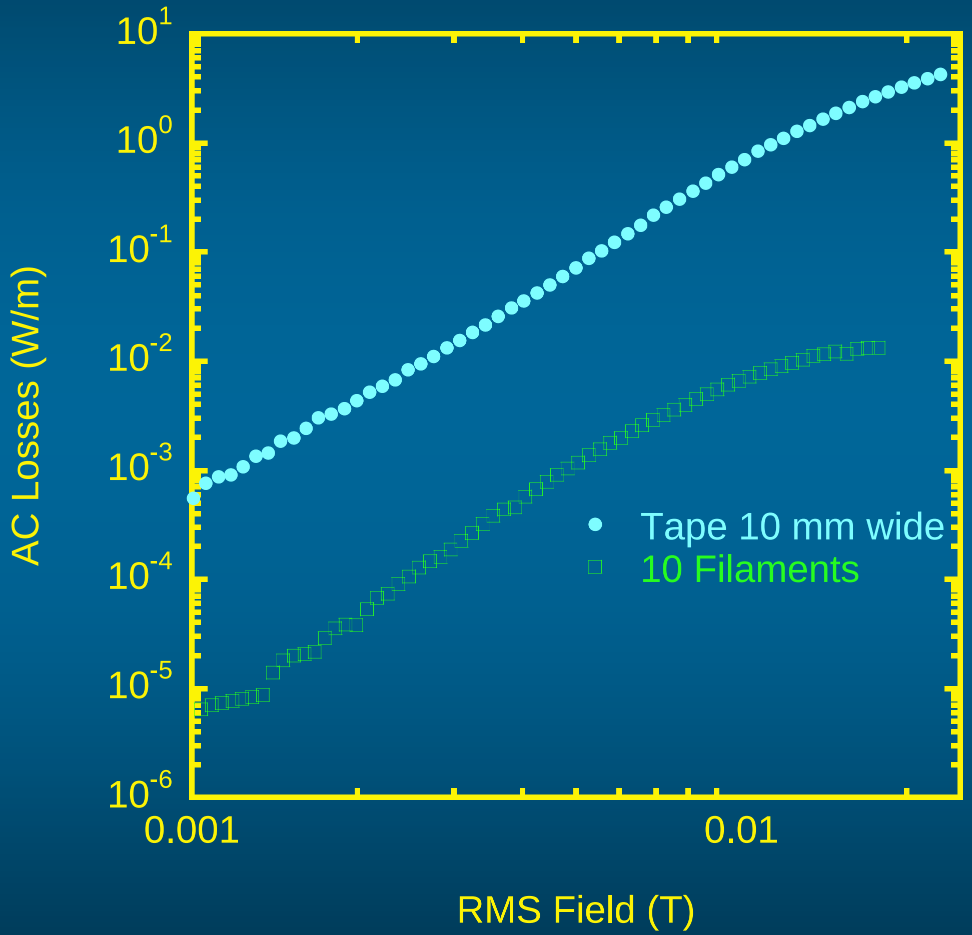
Total losses significantly reduced

- Magnetic losses tape 10mm



Total losses significantly reduced

- Magnetic losses tape 10mm
- 10 filaments + 5 cross-cuts/m
  - 2 orders of magnitude reduction



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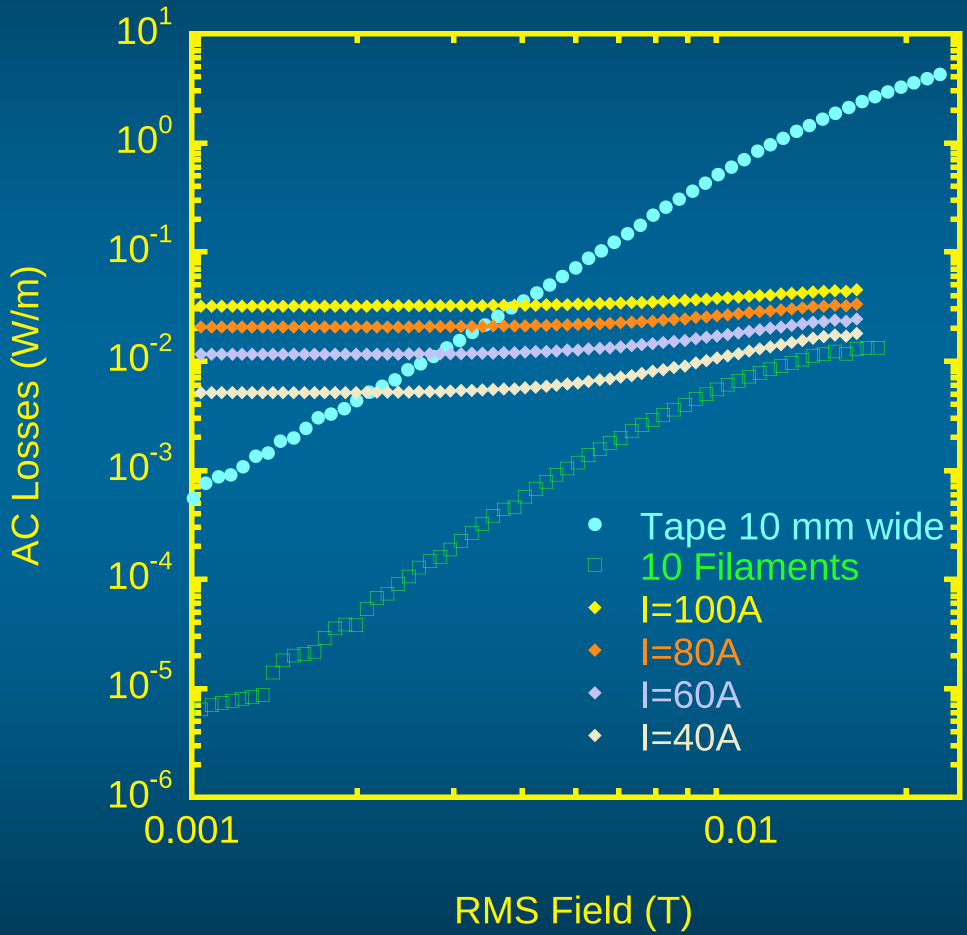
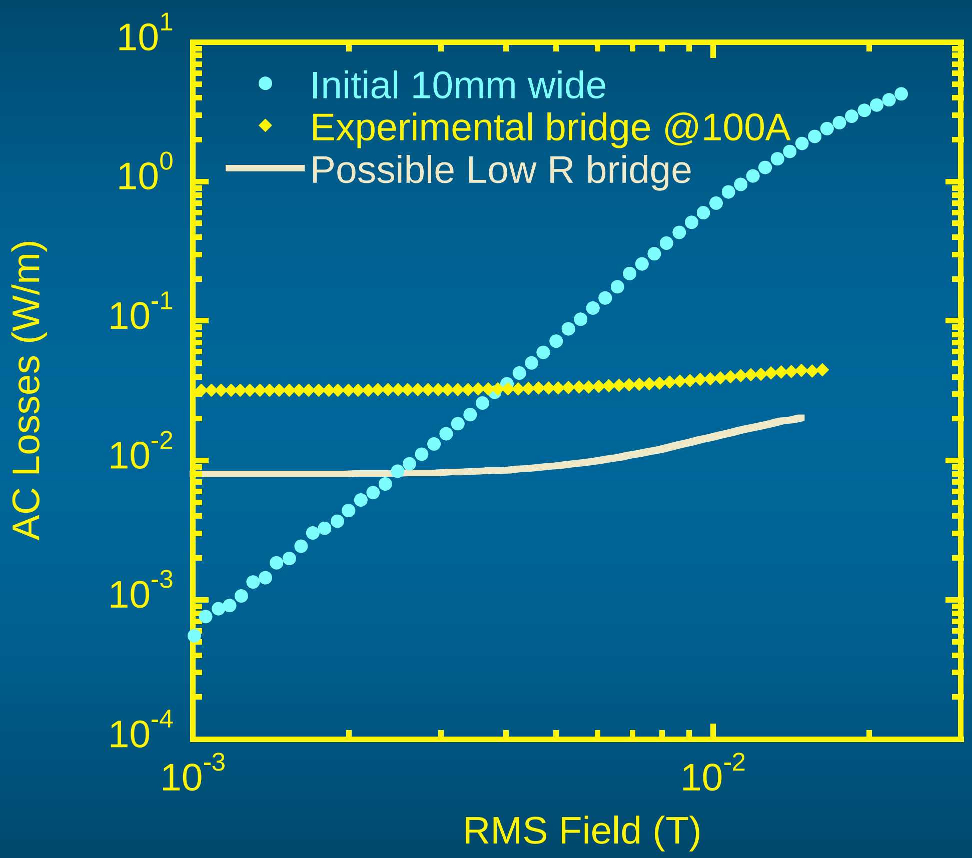
Total losses significantly reduced

- Magnetic losses tape 10mm
- 10 filaments + 5 cross-cuts/m
  - 2 orders of magnitude reduction
- Transport current: RI^2 contribution of the bridge



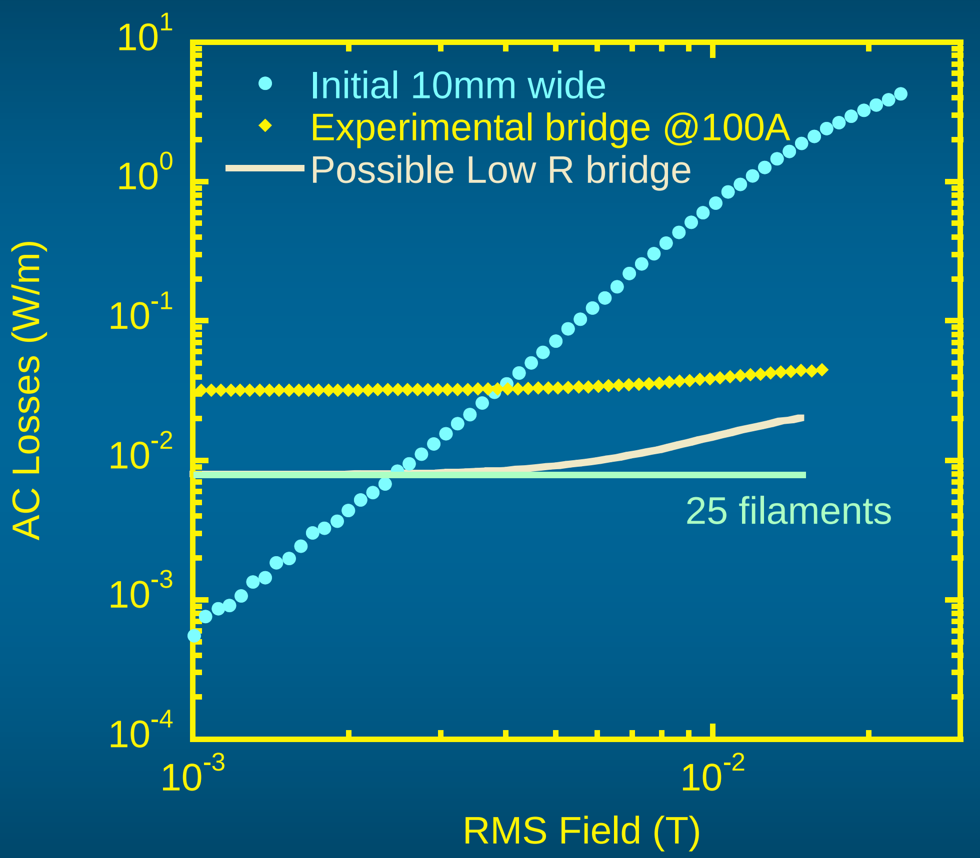
Even greater loss reduction is possible

- Possible further improvements
  - reducing the resistivity of the cross-cut to $0.4 \mu\Omega \cdot \text{cm}$ (FEM)



Even greater loss reduction is possible

- Possible further improvements
  - reducing the resistivity of the cross-cut to 0.4μΩ·cm (FEM)
  - 25 filaments
- Even better at higher frequencies (ohmic loss is frequency independent)



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Summary for individual tapes

- We have
  - Demonstrated a loss reduction of nearly **2 orders of magnitude** (100 A, 10mm wide, 30mT peak)
  - Indicated a way for loss reduction **of 2 to 3 orders of magnitude** (100 A, 10mm wide, 30mT peak)

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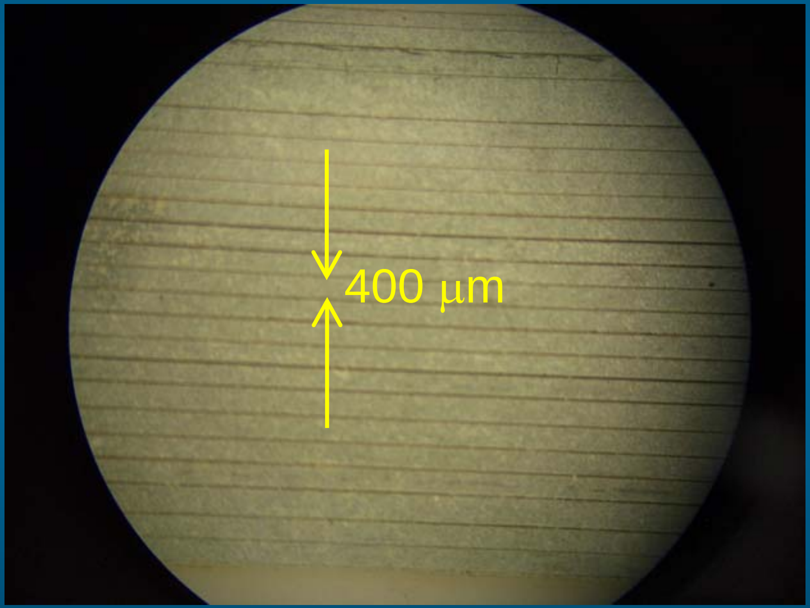
Twisting requirement relaxed

- Still need a twist
  - Zero net flux threading superconductor
  - Otherwise eddy currents generated
- Previously twist pitch ~cm
  - Not easy in tapes
- Now twist once every turn only (also suggested by Sumption et al., proceedings of Applied Superconductivity Conference 2004)
- High symmetry coils – no twist required

Manufacturability is good

- Introduced a technique for cutting long samples into many filaments in a short time
- Mechanical scribing with microtome blades
  - Continuous process
  - Low additional cost
  - 25 filaments, 10 mm wide
  - Speed ~ 1 meter/min
  - Details in 'Wire Session' talk by Gibbons, Matias and Ashworth



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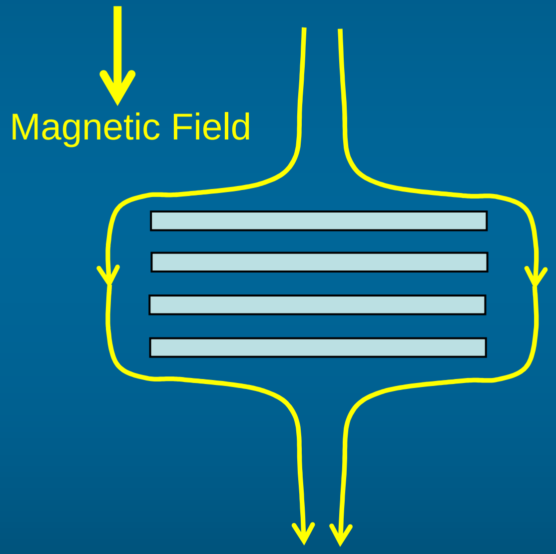
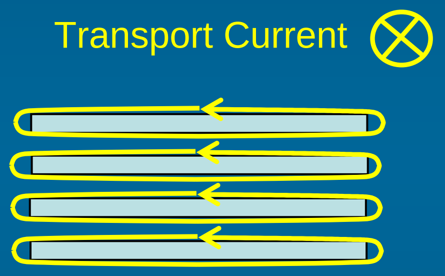
Beyond individual tapes

- So far we have considered loss reduction in individual tapes
- Real devices are assemblies of several tapes
- Electromagnetic interaction makes things more complicated

Stacking multiple tapes changes losses

- Analytical models (for infinite stacks)
  - Applied field — losses decrease with decreasing separation
  - Transport current — losses increase with decreasing separation





- Is there an optimum separation with reduced losses?
  - Analytical models: no, transport losses dominate
  - What does FEM say?

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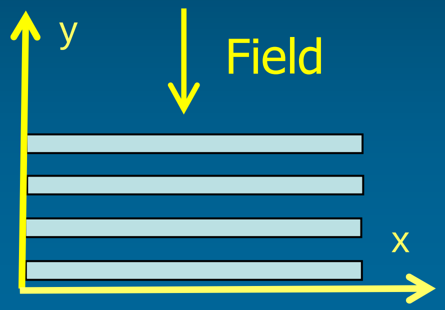
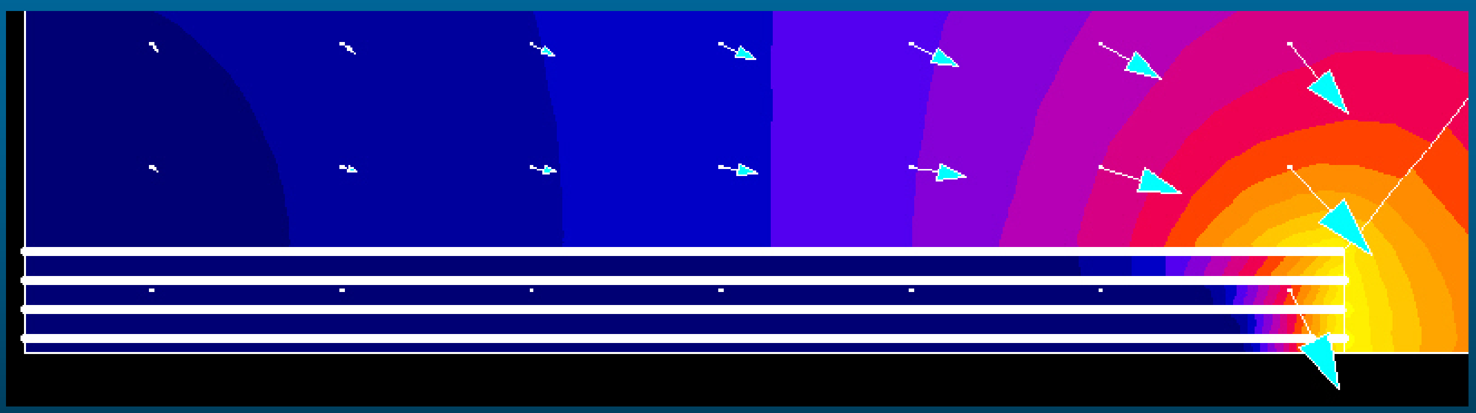
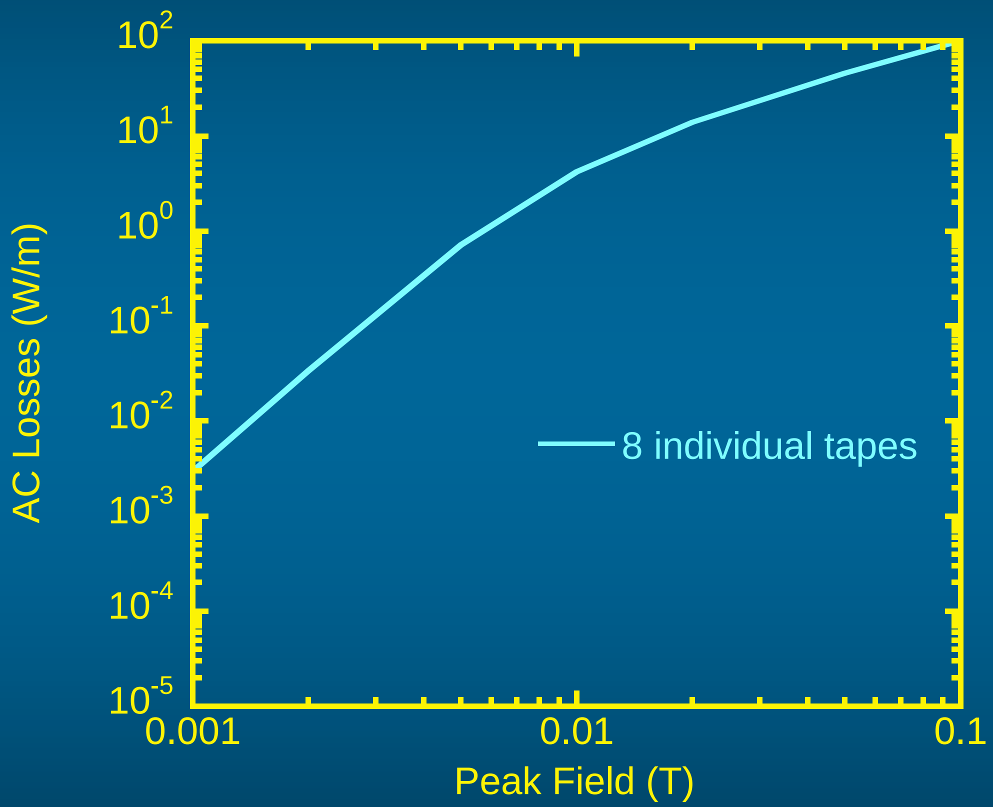
FEM simulations of a 8-tape stack





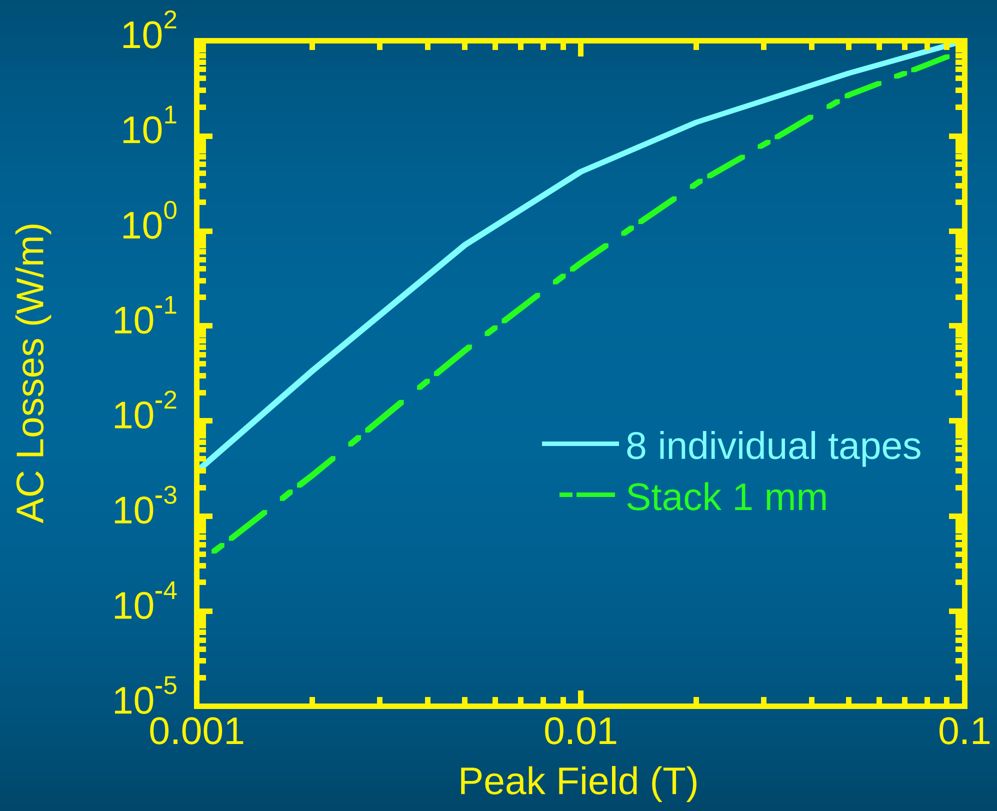
FEM indicates losses per tape decrease significantly as tape separation decreases

- 8 individual tapes



FEM indicates losses per tape decrease significantly as tape separation decreases

- 8 individual tapes
- Stack 1 mm separation
  - Loss reduction factor 10



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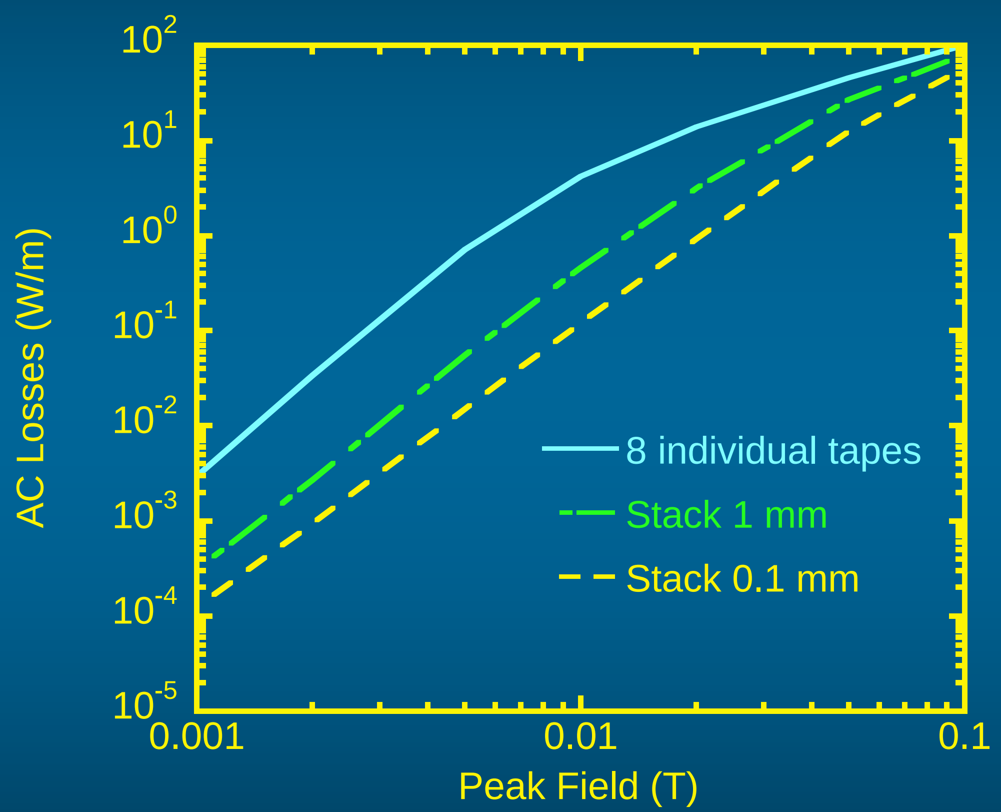
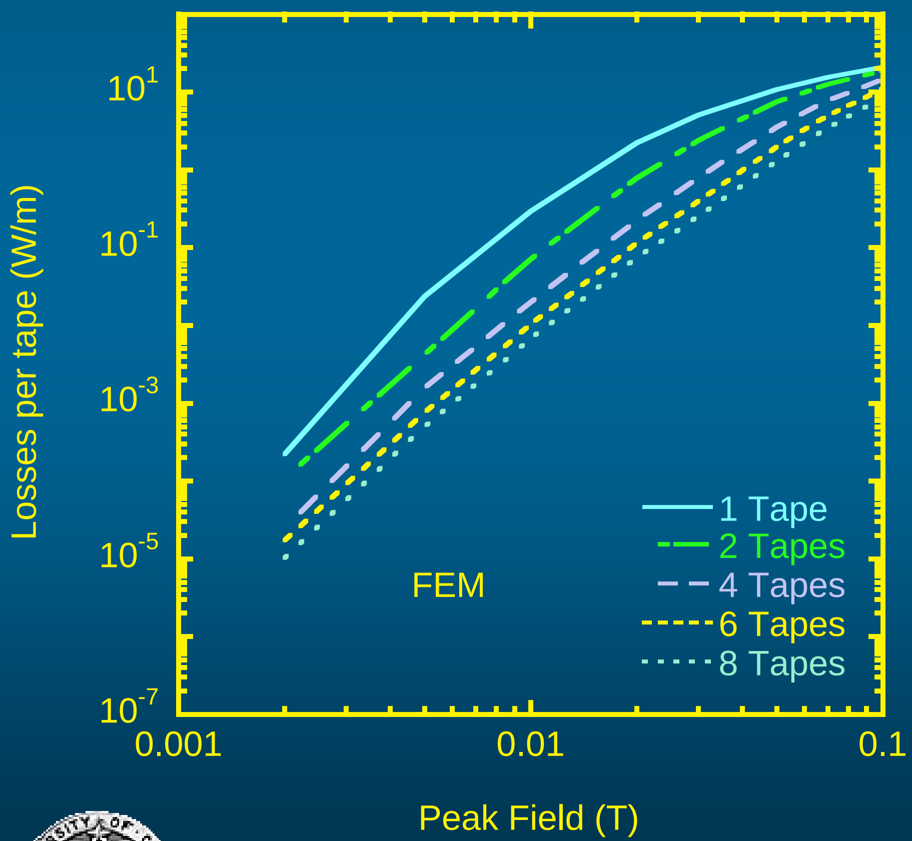
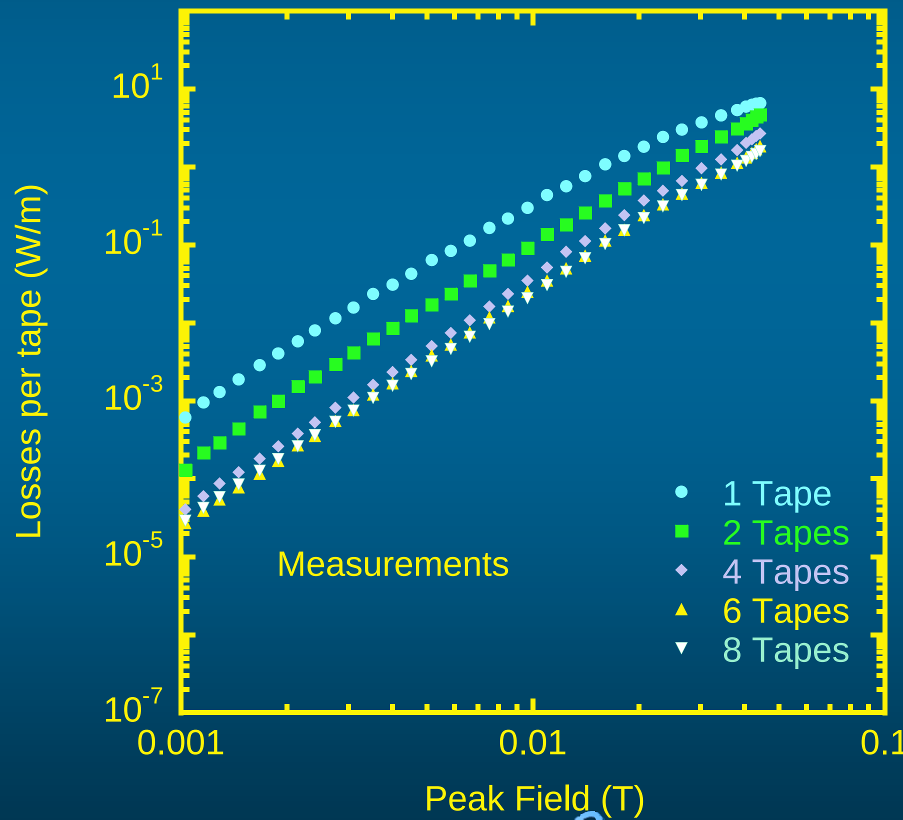
FEM indicates losses per tape decrease significantly as tape separation decreases

- 8 individual tapes
- Stack 1 mm separation
  - Loss reduction factor 10
- Stack 0.1 mm separation
  - Loss reduction factor 30



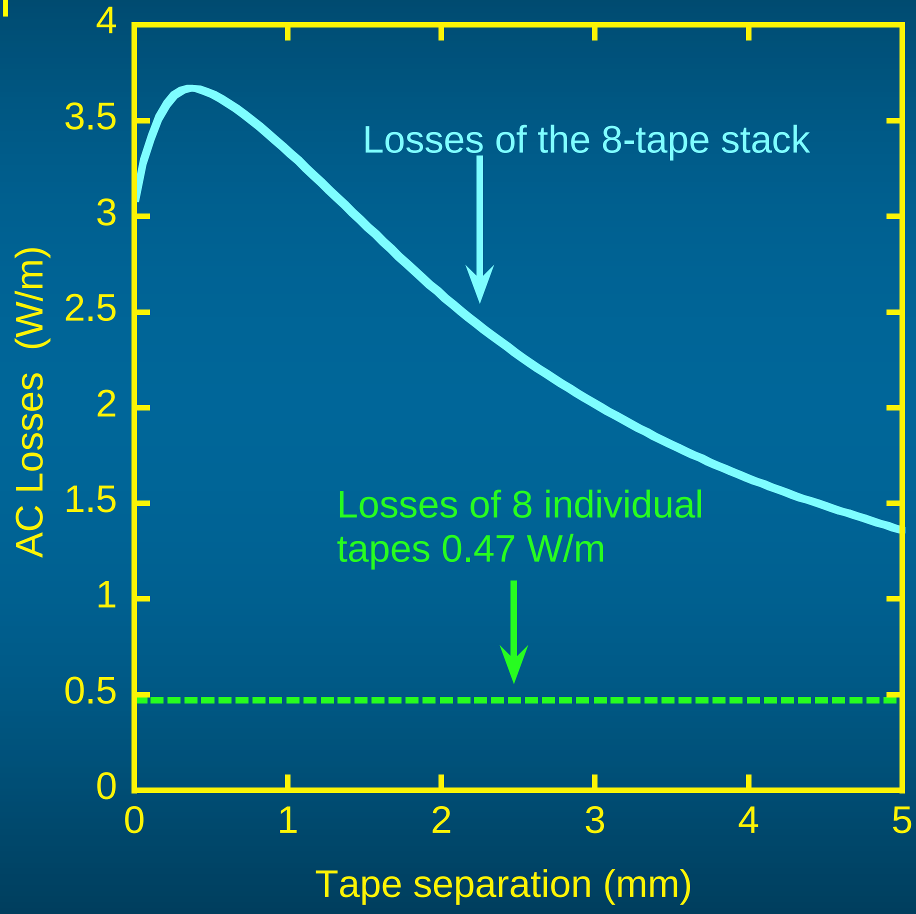
FEM and measurements show losses per tape decrease significantly as number of tapes increases





FEM indicates transport losses increase moderately as separation decreases

- Stack losses higher than the sum of isolated tapes
  - Factor 6-7 for 8-tape stack
  - Analytical models > 100
- FEM: loss increase not unreasonable and outweighed by reduction in magnetic losses



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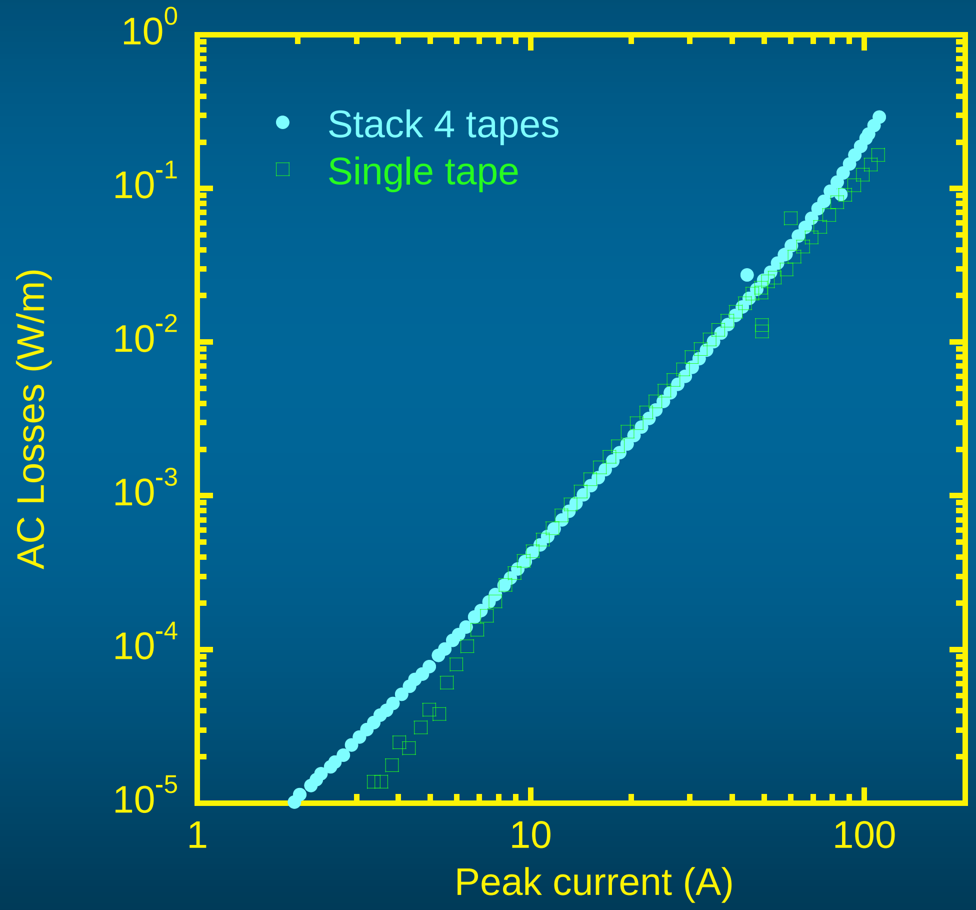
Measurements indicate no significant increase in transport losses

- No significant increase for 4 tapes, 0.2 mm separation
- Probably due to non-constant Jc(x)
- Not yet understood



FEM & measurements: yes, we can reduce losses

- Applied magnetic field
  - Loss decrease factor 10-30 for < 1 mm separation
- Transport current
  - Loss increase factor 6-7 for < 1 mm separation
- There is a window of reduced losses for current and field applications

Plans and Goals FY 2005: *from 2004 presentation*

1. Not to present this talk to you next year!
   - Present it in "wire session"
   - AC loss reduction a central part of coated conductor development
2. Develop and test conductor architecture
   - Capable of carrying 100A/cm width ac current in 100mT ac field without quenching (present limit is 10mT)
   - Capable of carrying 100A/cm width ac current in 10mT ac field with ac losses **TWO** orders of magnitude below present values.
3. Develop and test a conductor production technique (lengths > 10cm)
   - Capable of carrying 100A/cm width ac current in greater than 10mT ac field without quenching.
   - Capable of carrying 100A/cm width ac current in 10mT ac field with ac losses **ONE** order of magnitude below present values.

Performance

1. Not to present this talk to you next year! **(half achieved!)**
   - ✓ Present it in "wire session"
   - ✓ AC loss reduction a central part of coated conductor development
2. Develop and test conductor architecture
   - ✓ Capable of carrying 100A/cm width ac current in 100mT ac field without quenching (present limit is 10mT) **(see 'wire' talk)**
   - ✓ Capable of carrying 100A/cm width ac current ir **30mT** ac field with ac losses **1/100 of 2004** : values.
3. Develop and test a conductor production technique (lengths > 10cm)
   - ✓ Capable of carrying 100A/cm width ac current in greater than 10mT ac field without quenching. **(see 'wire' talk)**
   - ✓ Capable of carrying 100A/cm width ac current in **30mT** c field with ac losses **1/20 of 2004** values.

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Results

- Introduced loss modeling capability to US
- Integrated modeling and measurement
- Developed a low loss "cross cut" conductor based on structure invented at LANL
- Made and measured the cross cut conductor in >10cm length
  - Losses 5% of 'bare' conductor
- Showed possibility of cross cut conductor with losses <1%
- Introduced a simple technique for making multifilament CC
  - Made multifilament tapes >50cm long at 1m/minute
- Used modeling to understand losses in 'real' CC (Jc vary across tape)
- Used ac loss "signature" to aid in CC manufacture

Plans and Goals 2006

- Develop and test conductors ~10cm length having losses <0.1W/m when carrying 100A in 0.1T ac fields
  - Move up from ~10mT to more relevant fields
- Develop a route to conductors having losses <1W/m in ac fields to 1T
  - A real 'stretch' goal, but needed.
  - Will depend on maintaining Jc at 1T fields as well as low loss structure
- Develop technique for calculating losses in eg coils
  - How do we calculate losses in a ~1m scale coil based on hts films ~10^{-6}m thick
  - Merge macro and micro scale calculations.
  - Work with software developer
- Further extend and validate models
  - Check against experiment
  - In particular examine interaction of transport current
- Using ac loss to assess tape quality
  - Non-uniform Jc across tape, how much information can we obtain?

Research Integration

- Coated conductor materials in collaboration with
  - LANL IBAD team
  - IGC-Superpower
  - American Superconductor Corporation
  - ITN
- DARPA funded program
  - American Superconductor Corporation/Office of Naval Research
- Air Force funded STTR Collaboration
  - Long Electromagnetic Industries
- EPFL Switzerland (two joint papers)
- US-Japan AC Loss collaboration (and successor)
- Patent

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